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Autonomous and Lagrangian Ocean Observations for Atlantic Tropical Cyclone Studies and Forecasts

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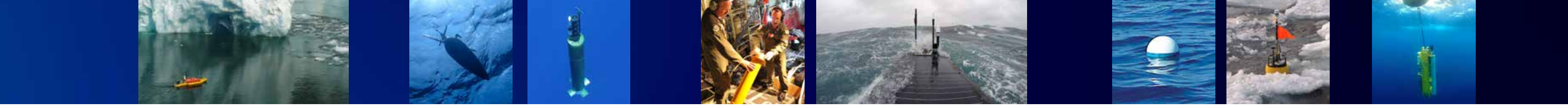
Image of Hurricane Gonzalo taken from the International Space Station by European Space Agency astronaut Alexander Gerst on October 16, 2014. *Image Credit: Alexander Gerst/ESA/NASA*



> "Gliders, profiling floats, and drifters deployed in the tropical Atlantic during hurricane season continue to provide upper-ocean and atmospheric observations that are key to initializing numerical ocean-atmosphere coupled forecast models, to properly identifying areas that may be responsible for storm weakening and intensification, and to improving intensity forecasts."

ABSTRACT. The tropical Atlantic basin is one of seven global regions where tropical cyclones (TCs) commonly originate, intensify, and affect highly populated coastal areas. Under appropriate atmospheric conditions, TC intensification can be linked to upper-ocean properties. Errors in Atlantic TC intensification forecasts have not been significantly reduced during the last 25 years. The combined use of in situ and satellite observations, particularly of temperature and salinity ahead of TCs, has the potential to improve the representation of the ocean, more accurately initialize hurricane intensity forecast models, and identify areas where TCs may intensify. However, a sustained in situ ocean observing system in the tropical North Atlantic Ocean and Caribbean Sea dedicated to measuring subsurface temperature, salinity, and density fields in support of TC intensity studies and forecasts has yet to be designed and implemented. Autonomous and Lagrangian platforms and sensors offer cost-effective opportunities to accomplish this objective. Here, we highlight recent efforts to use autonomous platforms and sensors, including surface drifters, profiling floats, underwater gliders, and dropsondes, to better understand air-sea processes during high-wind events, particularly those geared toward improving hurricane intensity forecasts. Real-time data availability is key for assimilation into numerical weather forecast models.

INTRODUCTION

The North Atlantic Ocean is an active basin for the genesis and intensification of tropical cyclones (TCs; Figure 1), with 11 named TCs, six hurricanes, and two to three major hurricanes forming between June and November in a typical year. These storms frequently affect highly populated coastal areas, causing large economic losses and having other societal impacts. Under appropriate atmospheric conditions, TC intensification and weakening have been linked to ocean properties, such as upper-ocean heat content (Mainelli et al., 2008) and stratification (Seroka et al., 2016), which can be estimated using both in situ and satellite observations. Assessment of the temperature of the upper 100 m of the ocean is linked to the amount of energy available for TC intensification (Price, 2009; D'Asaro et al., 2014; Glenn et al., 2016), together with other parameters, such as specific humidity and surface winds (Cione, 2015).

Coupled prediction models must accurately forecast the cooling of sea surface temperature (SST) beneath a TC to predict the enthalpy flux between the ocean and the atmosphere with sufficient accuracy to produce a credible intensity forecast. To achieve this goal, the oceanic component in a coupled prediction system must be initialized with an accurate three-dimensional representation of the ocean's dynamical features and the upper-ocean thermal structure associated with these features (Halliwell et al., 2011). A bias in the initial upper-ocean heat estimates will cause the coupled model to either overestimate or underestimate enthalpy flux from the ocean to the atmosphere, leading to biased intensity predictions. An inaccurate initialization of ocean mesoscale features will produce errors in the projected pattern of SST cooling beneath a storm (Halliwell et al., 2011).

The value of autonomous and Lagrangian platforms and sensors (ALPS) with respect to TC prediction is that they provide critically important in situ measurements at and/or beneath the ocean surface. Assimilation of ALPS measurements reduces the upper-ocean thermal bias and corrects errors in the representation of mesoscale features in the initial oceanic fields. Dong et al. (2017) demonstrate the positive impact of assimilating oceanic observations on ocean model initialization and TC intensity forecasts. ALPS are also important for evaluating ocean model performance, devising strategies to improve their performance, and potentially characterizing the upper ocean's response in all four quadrants of a TC, particularly within the inner-core region where observations are rarely available.

Recent air-sea interaction programs have illustrated the importance of ocean observations using ALPS, particularly the Coupled Boundary Layer Air-Sea Transfer (CBLAST) program (Black et al., 2007; Chen et al., 2007; Sanford et al., 2007) and the Impact of Typhoons on the Ocean in the Pacific (ITOP) program (Mrvaljevic et al., 2013; D'Asaro et al., 2014). These experiments used a variety of air-deployed ALPS, in particular, surface drifters, profiling floats, thermistor chains, and surface wave buoys. For example, an upper-ocean response analysis that used EM-APEX profiling floats deployed ahead of Hurricane Frances (2004) as part of the CBLAST program demonstrated the importance of using repeat ocean profilers to study the physics of the upper ocean's response to a storm (Sanford et al., 2011), confirming the theoretical model developed by Price (1981). Air-deployed Lagrangian floats equipped with ambient noise sensors measured wind speed and rainfall during the passage of Hurricane Gustav (2008) during CBLAST and Typhoons Megi (2010) and Fanapi (2010) during ITOP, demonstrating the maturation of the Wind Observations Through Ambient Noise (WOTAN) technique (Zhao et al., 2014). Air-deployed surface drifters also played a critical role during these field programs by showing that drag coefficient behavior changes as it saturates at high wind speeds and may even decrease (Zedler et al., 2009). Wu et al. (2015) used a coupled prediction model in conjunction with ITOP atmospheric and oceanic observations to study air-sea interaction in Typhoon Megi (2010). These field programs collectively show the importance of integrating subsurface ocean observations with atmospheric and air-sea flux measurements to identify and understand the key physical processes controlling air-sea coupling in TCs and for evaluating and improving the representation of this coupling in models.

Despite these recent advances in understanding the role of the upper ocean in TC intensification, errors in tropical Atlantic TC intensity forecasts have not

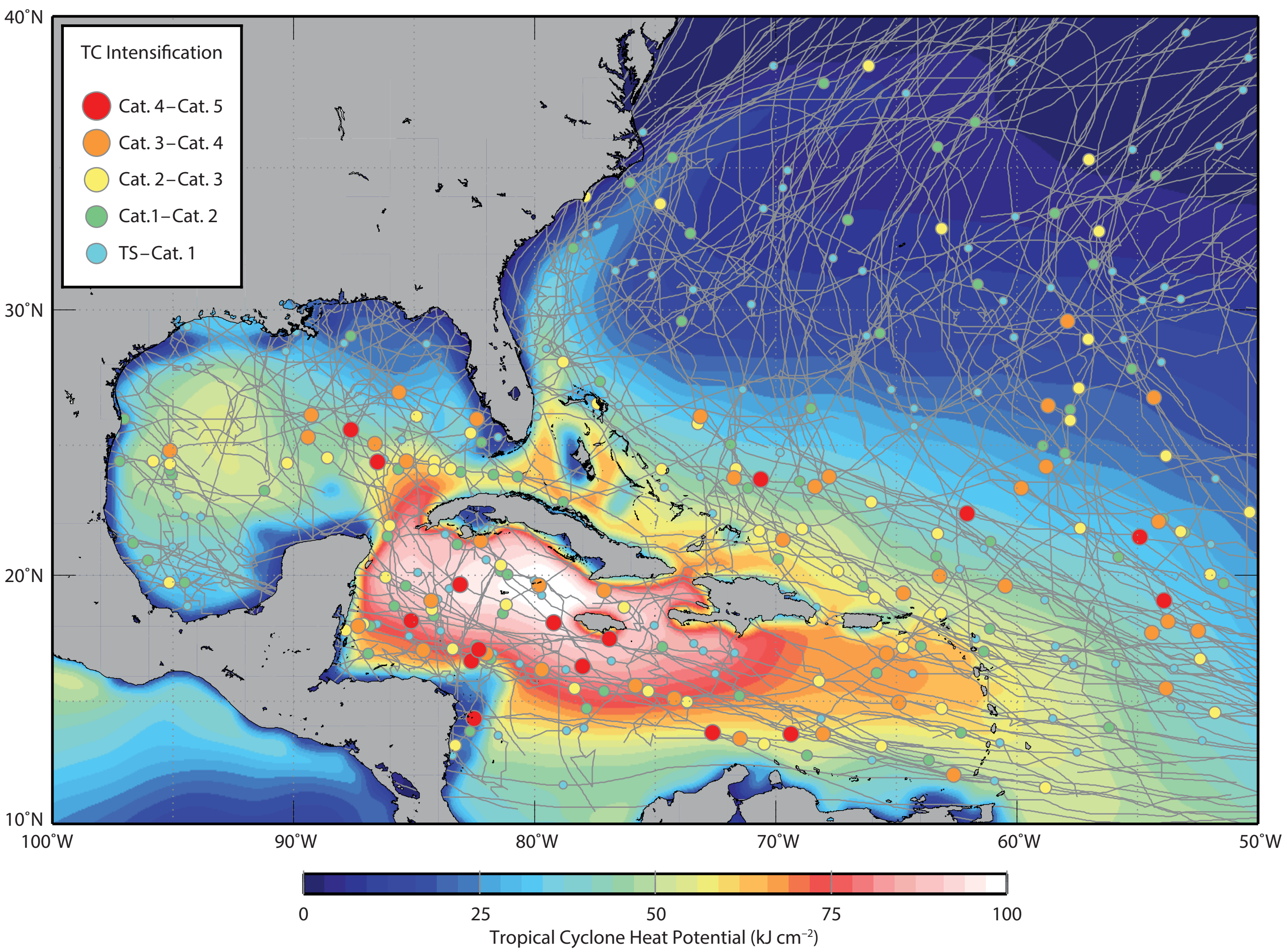


FIGURE 1. Atlantic tropical cyclone tracks during the period 1993–2010, with colored circles indicating the position where they intensified. The background color shows the average Tropical Cyclone Heat Potential (upper ocean heat content above 26°C isotherm) during the same period.

been significantly reduced (Figure 2). One factor contributing to the lag in improvement of TC intensity forecasts relative to TC track forecasts is the lack of a dedicated ocean observing system with sustained and targeted ocean observations to better represent the ocean component in ocean-atmosphere coupled intensity forecast models. Here, we discuss several recent efforts that have used a suite of observational tools—drifters, profiling floats, gliders, and dropsondes—to better understand upper-ocean processes and air-sea interactions during high wind events with the specific goal of improving hurricane intensity forecasts. A few examples are provided for how observations from each platform have been used in the forecasts. We also suggest potential future roles for ALPS in TC forecasting.

SAMPLING WITH ALPS IN TROPICAL CYCLONES

A variety of autonomous and Lagrangian platforms have been used in recent years to assess upper-ocean and air-sea interface conditions before, during, and after the passage of TCs (e.g., Zedler et al., 2009; Centurioni, 2010; Sanford et al., 2011; Hormann et al., 2014; Rudnick, 2016). Some platforms have been used for targeted TC sampling, while others are components of the sustained Global Ocean Observing System (Legler et al., 2015). By virtue of their autonomy, temporal and spatial sampling, and ability to return near-real-time ocean observations under high wind and wave conditions, these platforms provide critical information about upper-ocean structure and atmospheric conditions. These in situ observations are usually used along with satellite-derived observations to complement efforts to forecast TC evolution (Lin et al., 2012).

Drifters

Multiple types of drifters provide oceanic and atmospheric observations during TCs. Sustained in situ hourly observations of SST and sea level atmospheric pressure (SLP) are provided by Surface Velocity Program (SVP) drifters deployed in support of the US National Oceanic and Atmospheric Administration's (NOAA's) Global Drifter Program. SVP Wind (SVPW), or Minimet, drifters are often air-deployed in front of TCs to measure 15 m depth currents, SSTs, SLP, and surface winds. Surface winds are measured with sonic anemometers. Wind direction is measured by an internal compass integrated into the drifter controller with an accuracy of ±2°. The Autonomous Drifting Ocean Station (ADOS) is an air-deployable drifter in which the drogue is replaced by a 150 m-long thermistor chain with pressure and temperature sensors spaced 10 m apart and sampling every 15 minutes. The subsurface pods use inductive communication technology to send their data to the drifter controller through the tether. During hurricane season, SVPW and ADOS drifters are air-deployed in front of TCs that are expected to impact the US mainland. A forecasted track is used to identify a deployment transect that intercepts the storm track at a right angle. The length of the transect depends on the width of the cone of uncertainty, but it typically ranges between 300 km and 500 km. In general, more ADOS drifters are deployed on the right-hand side of the storm track to measure mixing induced by the more intense winds in the cold wake of the TC. In the past 15 years, air deployments of drifters have been conducted in the Atlantic Ocean during Fabian (2003), Frances (2004), Rita (2005), Dean (2007), Gustav (2008), Ike (2008), and Isaac (2012), and in the Western Pacific Ocean during Hagupit (2008), Jangmi (2008), Fanapi (2010), and

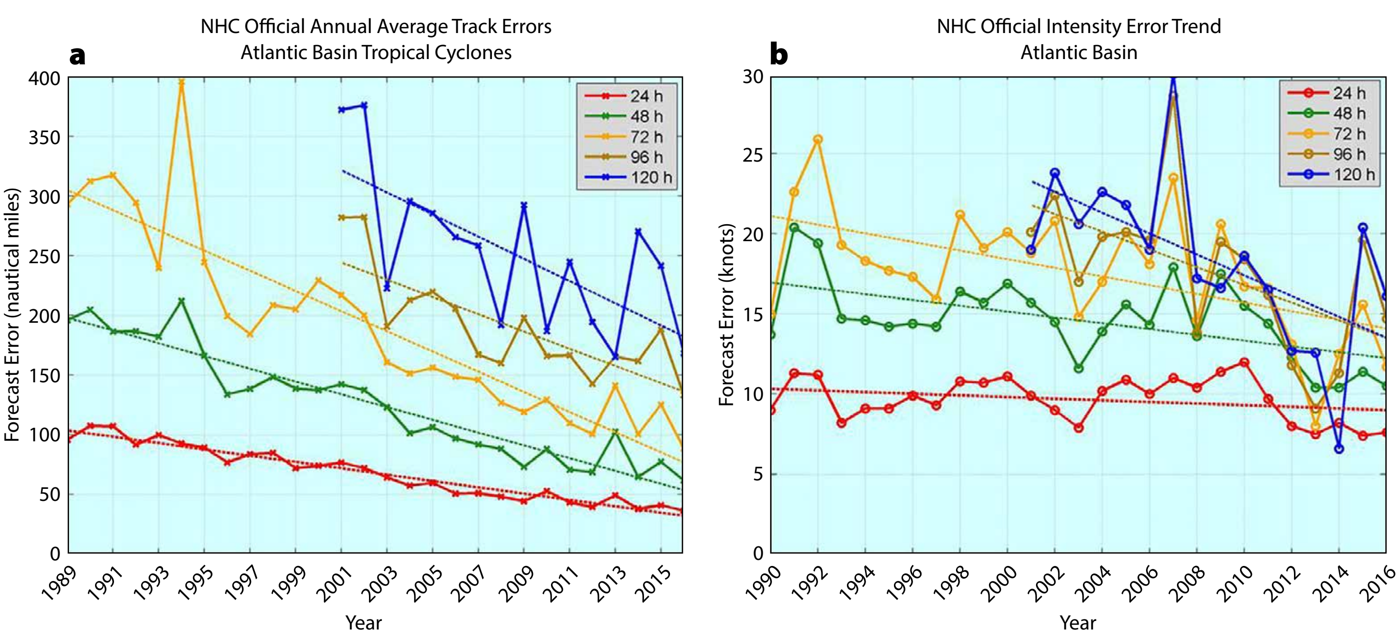


FIGURE 2. Errors in (a) track and (b) intensity forecasts of the US National Oceanic and Atmospheric Administration's (NOAA's) official forecasts for tropical cyclones in the tropical Atlantic. *Source: http://www.nhc.noaa.gov/verification/verify5.shtml*

Malakas (2010). In total, 207 drifters have been deployed with a success rate of 92%. These drifters have provided data in one of the most challenging ocean environments, with TCs ranging from Category-1 to Category-5 intensity.

Profiling Floats

Standard profiling floats (e.g., those used in the Argo Program; see Riser et al., 2016) offer the advantage of providing a long time record in the ocean. They can also be deployed far ahead of storms by a suitable platform. However, given forecast track uncertainties and long transit times for ships, it is difficult to target ocean observations for any particular storm. For these reasons, an air-deployable profiling float, the ALAMO (Air-Launched Autonomous Micro-Observer), was developed (Jayne and Bogue, 2017, in this issue). ALAMO floats conform to the Hurricane Hunter aircraft size A sonobuoy launch system. This versatility permits their deployment during operational TC reconnaissance missions tasked by the US National Hurricane Center in a similar manner to how Air-deployable eXpendable BathyThermographs (AXBTs) are deployed (Sanabia et al., 2013). One ALAMO float can provide hundreds of temperature profiles over time, delivering a long-term observational capability before, during, and after a storm. ALAMO floats can also carry additional sensors, such as for pressure and salinity, as well as accelerometers for surface wave field observations. A total of 60 ALAMO floats equipped with temperature and pressure sensors were deployed during the three hurricane seasons between 2014 and 2016 in support of tasked TC reconnaissance missions in both the Atlantic (Figure 3) and the eastern North Pacific basins. Figure 4 shows the ocean response measured by ALAMO float 9068 deployed on October 3, 2015, ahead of Hurricane Joaquin. The changes in profiling frequency and depth show the programmable capability of the float mission parameters.

Underwater Gliders

Autonomous underwater gliders are used for observations in the vicinity of TCs over continental shelves, near islands, and in the open ocean, collecting observations in either targeted or sustained mode. Some gliders are deployed for the duration of the Atlantic hurricane season (e.g., off Puerto Rico by the NOAA Atlantic Oceanographic and Meteorological Laboratory [AOML] and the Caribbean Coastal Ocean Observing System [CARICOOS], and off Bermuda by the Bermuda Institute of Ocean Science [BIOS]), while others are deployed in rapid response mode when storms threaten coastal regions (e.g., in the Middle Atlantic Bight continental shelf region by Rutgers University and the Woods Hole Oceanographic Institution [WHOI]). Because underwater gliders propel themselves horizontally, given sufficient lead time, they can be positioned strategically and can attempt to hold their stations during the passage of a storm. However, upper-ocean currents exceeding approximately 0.25 m s^{-1}, common during high wind conditions, may sometimes overwhelm a glider's ability to hold its position. Gliders typically carry more instrumentation than drifters or floats, often adding optical sensors for plankton or particulates, oxygen sensors, or small acoustic Doppler current profilers (Todd et al., 2017) to the standard CTDs. Measurements from these additional sensors can be used to investigate TC impacts on other environmental parameters. Gliders have sampled oceanic conditions during Atlantic hurricanes including Barry (2007), Irene (2011), Sandy (2012), Arthur (2014), Gonzalo (2014), Joaquin (2015), Hermine (2016), and Matthew (2016).

Dropsondes

Since its introduction in 1997, the Global Positioning System (GPS) dropsonde observing platform has been used by atmospheric scientists to study various weather and climate phenomena (Wang et al., 2015). In 2013, the dropsonde's atmosphere-only payload—measuring pressure, temperature, humidity, and winds—was upgraded by NOAA and the National Center for Atmospheric Research to include a sensor capable of

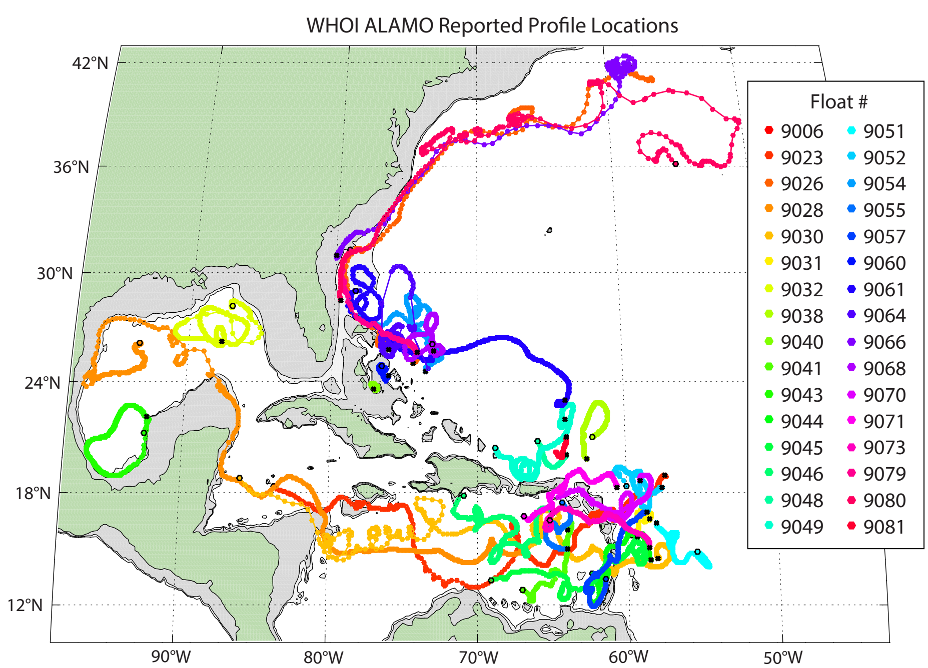


FIGURE 3. ALAMO (Air-Launched Autonomous Micro-Observer) float deployments in the Atlantic Ocean, Caribbean Sea, and Gulf of Mexico from 2014 to 2016. Additional plots are available at http://argo.whoi.edu/alamo.

estimating sea surface temperature. Over 200 of these special GPS dropsondes were built, of which 57 were deployed during Hurricane Edouard in 2014. This significant upgrade allowed scientists to simultaneously capture TC atmospheric structure and critical, co-located thermodynamic measurements at the air-sea interface for the first time. Prior to the development of this so-called "IRsonde," the only way to approximate coupled air-sea observations was to release a traditional, atmosphere-only GPS dropsonde followed by a separate air deployment of a much bulkier (and non-GPS-capable) bathythermograph.

During a three-day deployment between September 15 and September 17, 2014, 30 IRsonde-bathythermograph pairs were deployed in Hurricane Edouard. Analysis of these data depicted a fairly weak correlation ($R^2 = 0.472$) between IRsonde-derived SSTs and SSTs obtained by the bathythermographs. However, after a detailed comparison of coincident radar reflectivity data from NOAA's P-3 Hurricane Hunter aircraft, further analysis revealed that IRsonde SSTs incorporated a significant cold bias relative to bathythermograph SSTs in conditions of moderate to heavy rain (i.e., reflectivity >20 dBz). A comparison of 16 SST pairs without rain contamination exhibited a much-improved correlation between the two observing platforms ($R^2 = 0.901$). These results suggest that IRsondes can be used to measure SSTs in TC conditions of light to no rain. It should also be noted that IRsonde-measured SSTs within the TC eye were in good agreement with SSTs obtained from co-located bathythermographs. As such, IRsonde SSTs sampled in the eye can also be used to represent SST conditions observed within the adjacent TC eyewall environment. As a direct result of these promising findings, the IRsonde sensor will be incorporated into other observing platforms, including unmanned aircraft systems (UAS). Beginning in the fall of 2017, remote SST measurements within the hurricane environment will be collected using the autonomous UAS *Coyote* (Cione et al., 2016).

Real-Time Data

Each of these observing platforms returns observations in near-real time. For their measurements to be useful for TC forecasting, they must be made available to forecasters in a timely manner. Most of the platforms transmit their data to the Global Telecommunication System (GTS), from which users running operational forecasts can retrieve and assimilate the data. Both SVPW and ADOS drifters return their data in near-real time through the GTS; data are also available through ftp and web application services from the Lagrangian Drifter Laboratory at the Scripps Institution of Oceanography. Data from ALAMO floats are transferred via Iridium to a server where they are decoded and quality controlled and then sent to the GTS. Glider observations are transmitted via Iridium to operator base stations and then to the NOAA/Integrated Ocean Observing System Glider Data Assembly Center and onward to the GTS. Dropsonde data collected in TCs are distributed in real time from the sampling aircraft (e.g., NOAA P-3, Air Force C-130) via the GTS. In addition, a long-term GPS dropsonde data archive is available online at https://data.eol.ucar.edu/project/NOAA-DHA.

ALPS-ENABLED IMPROVEMENTS IN TC OCEAN-INDUCED DYNAMICS AND INTENSITY FORECASTING

Drifter observations have proven to be key for constraining satellite SST errors and biases (Zhang et al., 2009), improving numerical weather prediction (Centurioni et al., 2016; Horányi et al., 2017), and helping to estimate heat fluxes and the upper level atmospheric circulation. However, the impact of these drifter observations on TC forecasting still needs to be assessed. For example, 10 drifters were deployed ahead of Hurricane Isaac on August 26, 2012. Figure 5 shows their locations in the Gulf of Mexico, as well as their continuous observations of SLP, surface wind speed, and SST from August 26 to September 11, 2012. The center of Hurricane Isaac passed over the drifter

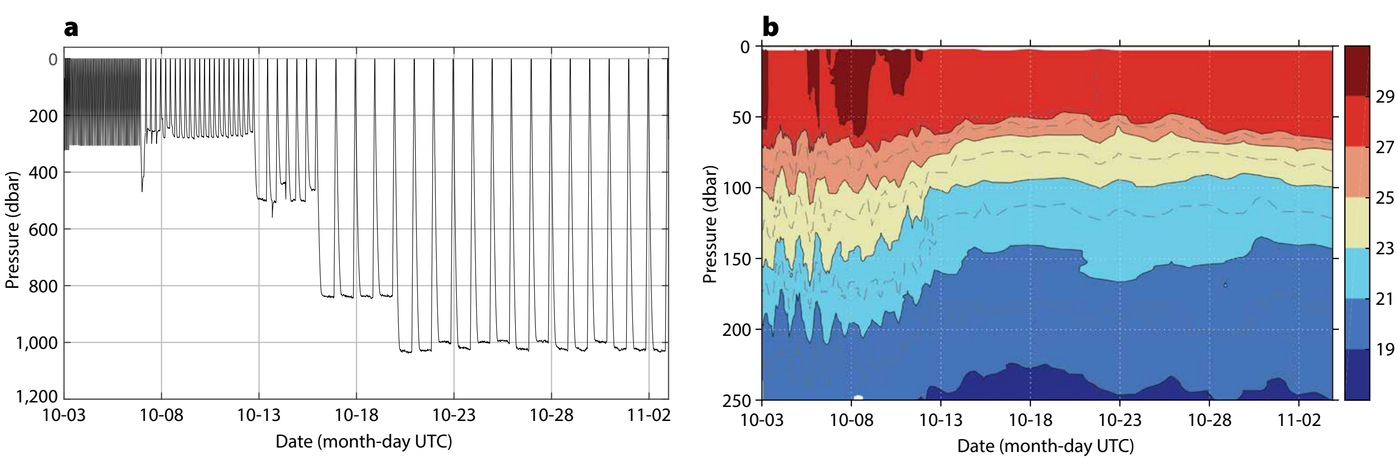


FIGURE 4. (a) Dive profile sequence for ALAMO float 9068 air-deployed during Hurricane Joaquin (2015), and (b) a temperature depth/time plot showing strong inertial oscillations created by Joaquin.

array between August 27 and August 30, and in situ observations from the array provided a unique, detailed description of the conditions before, during, and after Isaac. The high temporal resolution of the drifter data (every 15 min) proved to be invaluable in capturing the SLP at about 982 hPa and wind speeds >45 kts near the center of the storm. The continued observations in time provided a rare opportunity to document not only the pressure and wind structure in Isaac but also the storm-induced ocean cooling and post-storm recovery of SSTs in the Gulf of Mexico.

Analysis is ongoing for all of the ALAMO float data. Initial results from ocean data assimilation studies with the Coupled Ocean Atmosphere Mesoscale Prediction System for Tropical Cyclones (COAMPS-TC) model for a few TCs, including Matthew in 2016, have shown significant reductions in ocean forecast errors when ALAMO data are assimilated (Doyle et al., 2014; Chen et al., 2017).

A recent study by Dong et al. (2017) assessed the impact of underwater glider data and other in situ and satellite observations on the forecast of Hurricane Gonzalo (2014). This hurricane developed in the tropical North Atlantic on October 12, 2014, and then traveled ~85 km northeast of one glider deployed north of Puerto Rico by AOML and CARICOOS. As Gonzalo passed near the glider, it intensified from a Category-2 to a Category-3 hurricane (Figure 6a). Glider observations indicated that hurricane-induced SST cooling forced by Gonzalo was largely suppressed by the presence of a low-salinity layer in the upper 20 m of the ocean (i.e., a barrier layer; Domingues et al., 2015). The presence of this barrier layer may have favored the storm's intensification, as Gonzalo continued intensifying into a Category-4 hurricane (Goni et al., 2015).

Observations collected by the glider before (July 15 to October 13, 2015), during, and after the passage of Gonzalo were assimilated into the high-resolution Hurricane Weather Research and Forecasting (HWRF)-Hybrid Coordinate Ocean Model (HYCOM) coupled forecast system (Dong et al., 2017). Results indicated that assimilation of the underwater glider observations significantly improved the pre-storm thermal and saline model initializations, in particular, the barrier layer (Figure 6b). Errors in maximum wind speed (Figure 6c) and minimum pressure for the 126-hour forecast when Gonzalo's center was northeast of Puerto Rico were reduced approximately 50% by assimilating underwater glider and other ocean data, as well as satellite altimetry observations.

Hurricane Gonzalo then traveled close to Bermuda, where a BIOS glider monitored ocean conditions. The BIOS glider was gathering ocean data after the passage of Hurricane Fay (Figure 6a). Within the cold wake created by the two TCs, the glider observed a 4°C surface temperature drop, a 50 m deepening of the mixed layer, and breaking internal waves along its boundary. A key result obtained from the glider observations is that

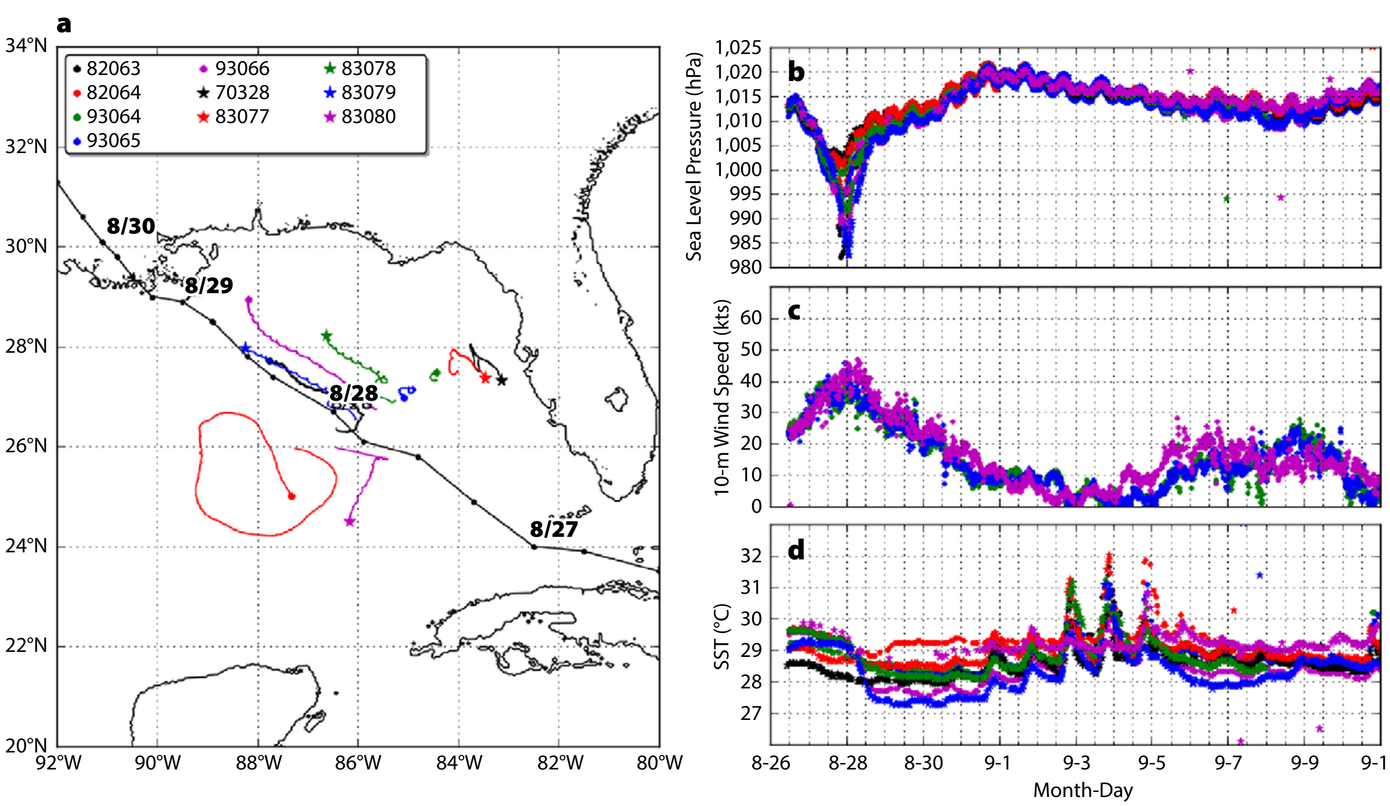


FIGURE 5. Summary of the observations from ten drifters deployed ahead of Hurricane Isaac on August 26, 2012. The (a) drifter positions/tracks and continuous observations of (b) sea level pressure (hPa), (c) surface wind speed (kts), and (d) sea surface temperature (SST, °C) are shown from August 26 to September 11, 2012.

Gonzalo weakened from a Category-4 to a Category-3 hurricane as it traveled over the cold wake produced by Fay.

One glider deployed five days ahead of the predicted landfall of Hurricane Sandy (2012) on the New Jersey coast also carried an acoustic Doppler current profiler, used for measuring vertical shear, to assess upper-ocean mixing (Miles et al., 2015). Observations from the glider showed that downwelling-favorable winds limited the supply of cold bottom water to be mixed upward as Sandy approached (Figure 7). The glider observations also showed that surface cooling was limited to 1°C–2°C (Zambon et al., 2014), contributing only slightly to the weakening of Sandy over the continental shelf. In the aftermath of Hurricane Sandy, the multi-institutional TEMPESTS (The Experiment to Measure and Predict East coast STorm Strength) program was initiated to collect ocean observations for improved intensity forecasts of storms impacting the US northeast using moorings, ALAMO floats, and gliders. TEMPESTS gliders measured the continental shelf's response to Hurricanes Arthur (2014) and Hermine (2016). Both storms caused cooling, mixed layer deepening, and westward flow over the continental shelf. Hurricane Arthur traveled through the region more quickly than Hurricane Hermine, which stalled and dissipated south of New England; only Hermine produced inertial oscillations following its passage (Figure 8).

Regional modeling of the continental shelf and slope with the Experimental System for Predicting Shelf and Slope Optics (ESPreSSO) is being used to develop improved data assimilation techniques to study the evolution of the temperature and density fields during storm passage. Glider data from Hurricanes Arthur (2014) and Hermine (2016) were assimilated into ESPreSSO to determine their impact. In addition, model forecasts were directly compared to glider data without their assimilation into ESPreSSO. In general, the short duration of the glider missions did not dramatically improve model forecast skill. This is likely due to the short time period of data collection before the storms. It is possible that longer-term glider observations obtained throughout hurricane season may improve forecast skill by better capturing the spatial and temporal variability of the pre-existing ocean state. Nonetheless, glider observations demonstrated the skill of the ESPreSSO system and the notably better representation of the mixed layer and thermal stratification relative to the Real-Time Ocean Forecast System (RTOFS).

SUMMARY AND OUTLOOK

A coordinated, multi-platform ocean observing system dedicated to monitoring ocean and atmospheric parameters to improve our knowledge of the complex processes that may be linked to TC intensification is not currently in place. Consequently, oceanographers and weather forecasters rely on the sparse, unevenly distributed observations from the climate-focused Global Ocean Observing System, which includes satellite observations. Satellite-derived fields of sea surface height and sea surface temperature, combined with in situ

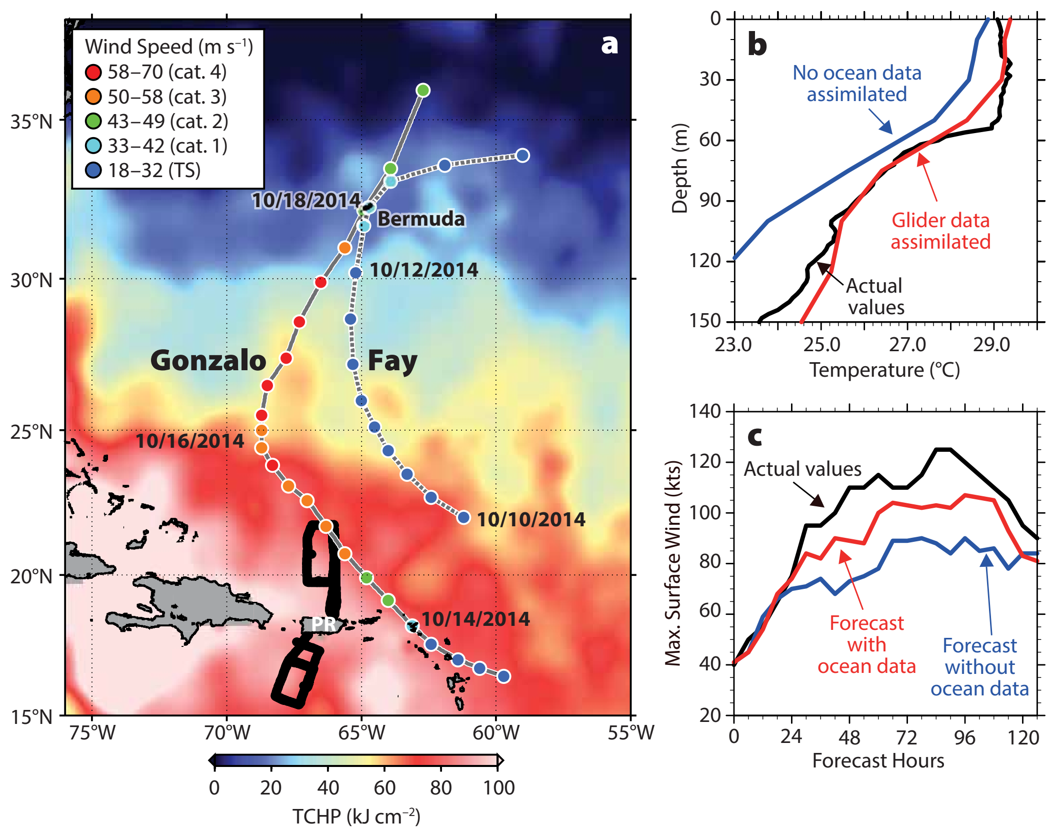


FIGURE 6. (a) Tracks of Hurricanes Gonzalo (2014) and Fay (2014) superimposed on the altimetry-derived upper ocean heat content (tropical cyclone heat potential) during October 2014. (b) Impact of glider temperature profiles on the initialization of the Hurricane Weather Research and Forecasting (HWRF)-Hybrid Coordinate Ocean Model (HYCOM) coupled forecast system. (c) Impact of glider and other ocean data in reducing errors in TC intensity (maximum wind speed) during the forecast of Gonzalo tested on October 13, 2014.

observations, have been shown to be the key to assessing conditions for TC intensification (Mainelli et al., 2008). The impact of in situ oceanic observations on intensity forecast errors has been quantitatively assessed for Hurricane Gonzalo (2014), where glider data improved the representation of the ocean component of the ocean-atmosphere coupled forecast model and reduced intensity forecast errors by almost 50% in the HWRF-HYCOM numerical model.

Gliders, profiling floats, and drifters deployed in the tropical Atlantic during hurricane season continue to provide upper-ocean and atmospheric observations that are key to initializing numerical ocean-atmosphere coupled forecast models, to properly identifying areas that may be responsible for storm weakening and intensification, and to improving intensity forecasts. ALPS provide a means to better understand the processes responsible for the rapid evolution of the ocean and its feedback on the atmosphere during the passage of TCs. During the 2017 Atlantic hurricane season, glider deployments are taking place in the Caribbean Sea, the Gulf of Mexico, and along the entire US East Coast. These observations, collected under a variety of programs, are being coordinated with NOAA's Hurricane Field Program.

Although gliders are being successfully deployed in rapid-response mode ahead of storms in the Atlantic Ocean, the logistical hurdles for such operations continue to be significant. With lead times typically less than a week based on forecast accuracy, gliders are deployed in rapid-response mode within two to three days of storm arrival. This short lead time may prevent comprehensive measurement of pre-storm conditions (e.g., complete cross-shelf transects) but allows for a more optimal placement of the gliders during storm passage. On the other hand, sustained glider observations carried out in locations where TCs often intensify or weaken can provide options to fill gaps where targeted deployments may present difficulties. However, targeted deployments of air-deployable profiling floats offer an attractive observing strategy. Because the floats can be deployed from Hurricane Hunter aircraft already tasked with storm surveillance, they are logistically easier to position along the forecast track ahead of a TC.

For modeling applications, the ideal strategy for improving intensity forecasts is to deploy multiple ALPS that gather repeat ocean profiles over a horizontal region at least as large as a typical TC diameter and with horizontal spacing sufficient to resolve ocean mesoscale structure. Observing System Simulation Experiments (OSSEs) that assimilate synthetic ocean profiler observations demonstrate that this horizontal spacing should be no more than one degree, and ideally 0.5 degrees, to resolve mesoscale structure (e.g., Halliwell et al., 2017a, 2017b). If this resolution is achieved along the predicted path of a storm by deploying a mix of ALPS, possibly supplemented by air-deployed ocean profilers, assimilation of these observations may substantially reduce ocean model initialization errors. Furthermore, they would provide repeat ocean profiles for all TC quadrants as a

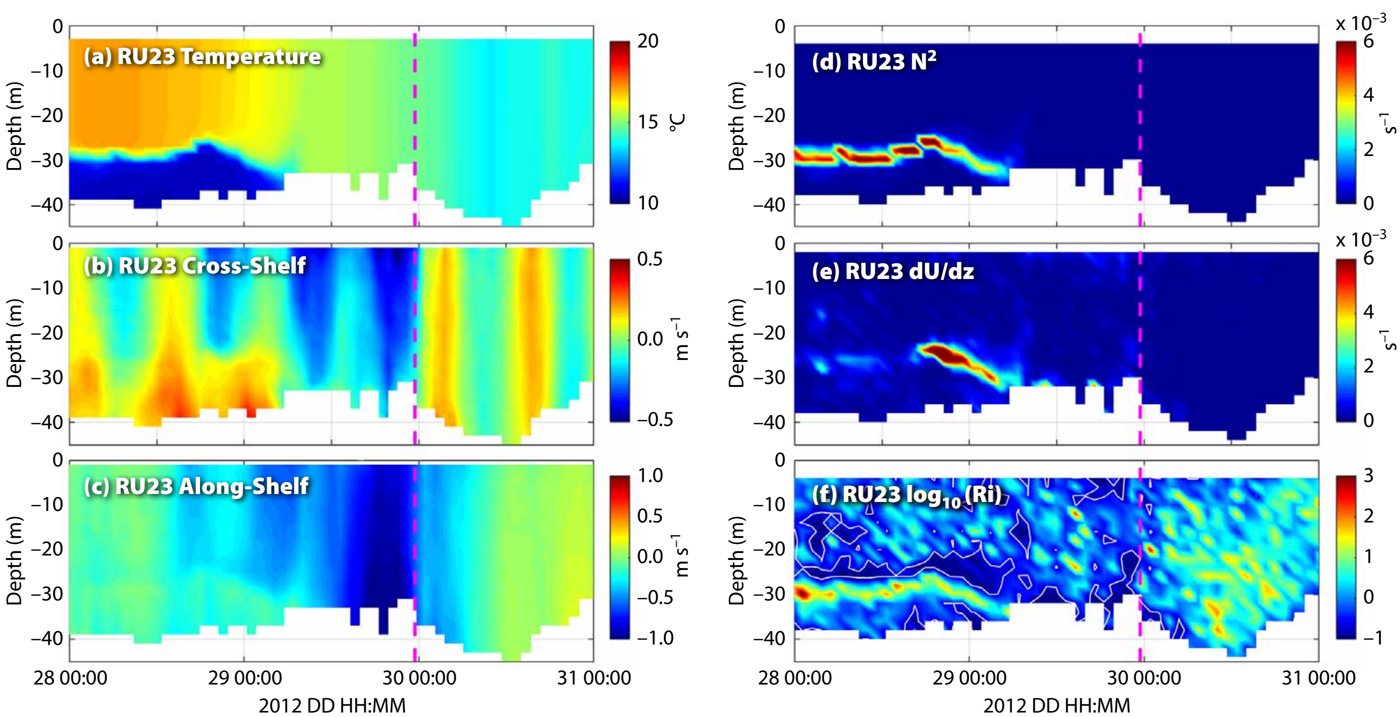


FIGURE 7. Rutgers University Glider 23 (RU23) time series of vertical profiles extracted during the Hurricane Sandy (2012) forcing period on the New Jersey Shelf. The dashed vertical magenta line indicates Sandy's landfall time. Variables plotted include (a) temperature, (b) buoyancy frequency, (c) cross-shelf velocity, (d) vertical shear of the horizontal velocity, (e) along-shelf velocity, and (f) the $\log_{10}$ of the Richardson number with a Richardson number of 0.25 plotted with white contours. Velocity color bars are different in panels (c) and (e) to highlight the larger along-shelf magnitudes.

storm passes over them for use in ocean model evaluation. This is particularly important for the inner-core region where subsurface ocean observations are rare.

For the 2017 hurricane season, novel air-deployable drifters measuring the directional properties of surface waves have been transitioned to operations. The addition of new sensors, such as relative humidity and air temperature, to the ADOS and Minimets atmospheric sensor packages could further improve

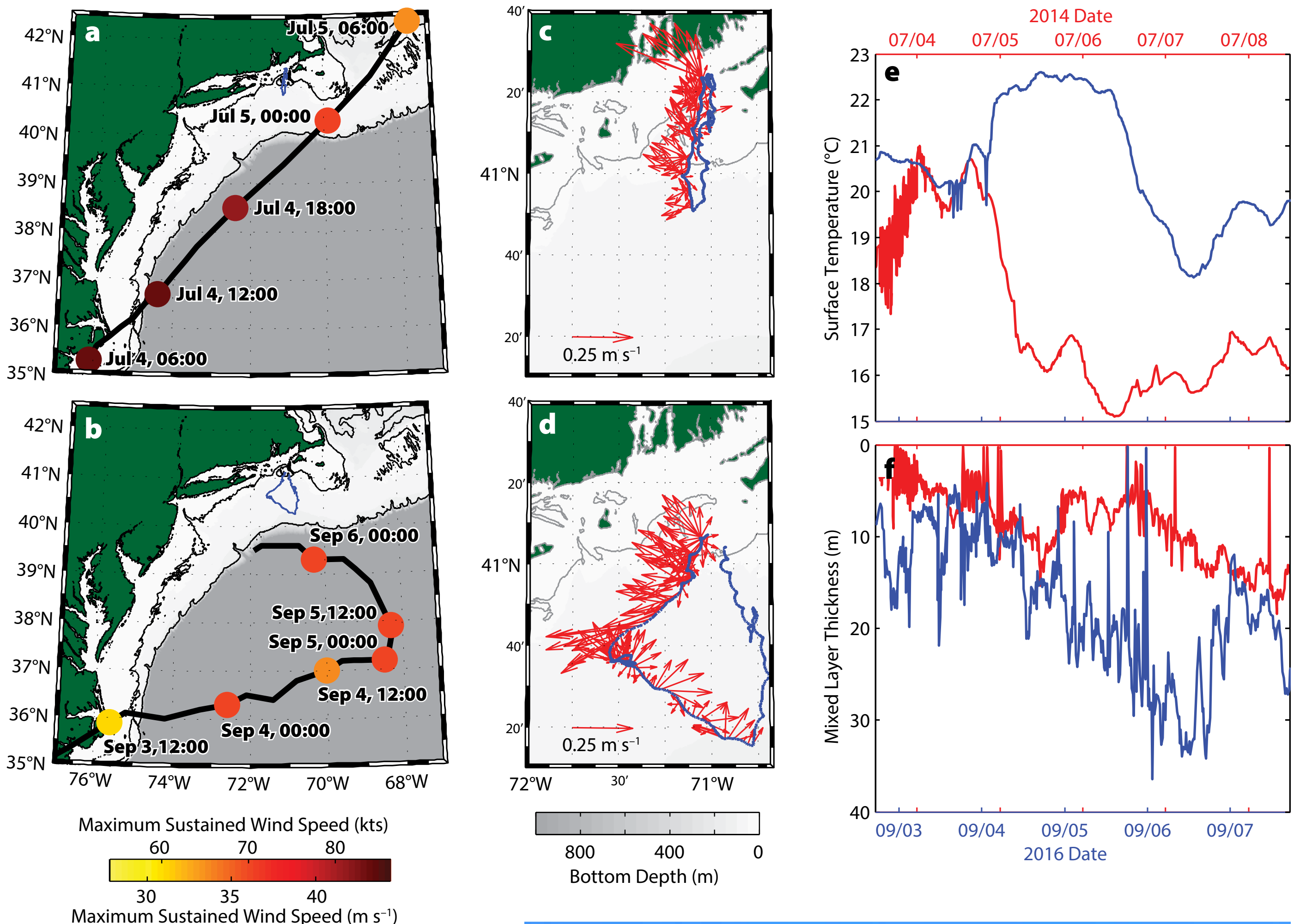


FIGURE 8. Glider observations of the effects of Hurricanes Arthur (2014) and Hermine (2016) in the Middle Atlantic Bight. Tracks of (a) Arthur and (b) Hermine with maximum sustained winds indicated by colors and tracks (blue) of Woods Hole Oceanographic Institution (WHOI)-operated gliders deployed in response to the storms. (c–d) Vertically averaged currents measured by the gliders before, during, and after the storms as the gliders moved offshore; only Hermine generated inertial oscillations (d). Time series of (e) surface temperatures and (f) mixed layer thicknesses measured by the gliders during Arthur (red) and Hermine (blue). (g) WHOI technician Sean Whelan deploying a Slocum glider over the continental shelf south of New England ahead of Hurricane Hermine (2016; trajectory in panel d). *Photo credit: Ken Kostel, WHOI*

quantification of the enthalpy fluxes and, consequently, of the intensity forecasts.

Enhancing the current atmosphere-only GPS dropsonde payload to include observations of the ocean is also expected to have multiple benefits related to TC intensity forecasting. By incorporating IRsonde technology into the existing GPS dropsonde platform, measurements of the coupled ocean model verification of SSTs and the mixed layer depth within the TC environment are likely to become routine. Coincident measurements of wind, temperature, moisture, and SST will also enable scientists to improve their understanding of both the magnitude and area distribution of surface fluxes of heat and moisture, especially under difficult-to-observe high wind hurricane conditions. Taken together, these advancements should enhance the physical representation of surface enthalpy fluxes found in current numerical models and, ultimately, improve future forecasts of TC intensity change.

Given the positive impact that upper-ocean observations collected by these observational platforms have demonstrated on TC intensity forecasts, the following recommendations are provided to further increase their contributions to improving Atlantic hurricane intensity forecasts:

- Continue assessing the quantitative impact of the upper-ocean's thermal and salinity (hence density) structure on TC intensification
- Assess the value of enhancing autonomous vehicle and Lagrangian observations in the Caribbean Sea, Gulf of Mexico, and tropical North Atlantic by adding dedicated platforms to the current network
- Develop a comprehensive autonomous vehicle and Lagrangian rapid response effort for upper-ocean heat content assessments prior to the passage of Atlantic TCs
- Perform numerical Observing System Experiments (OSEs) using actual observations and OSSEs using synthetic observations

There are seven regions in the global ocean where TCs originate and intensify. Although the results presented here focus exclusively on the tropical Atlantic basin, the recommendations listed above may also apply to the other six basins where TCs occur. Given the extent of these regions and the number of countries whose coastal areas are potentially impacted by TCs, a coordinated international effort in the design, implementation, maintenance, and data management of key aspects of ALPS observations may ensure the feasibility of logistical, operational, and research activities. In all regions, OSEs or similar numerical experiments will help to provide an assessment of the impact of upper-ocean observations on TC intensity forecasts, while OSSEs may later determine the optimal and most cost-effective deployment strategies for both targeted and sustained observations with respect to improving TC intensity prediction.

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